



This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under GA No 101004730.

# Target studies for the International Muon Collider Collaboration

Liverpool (UK), 1-6 Sept 2025, NuFact 2025

Rui Franqueira Ximenes, on behalf of the IMCC & CERN SY-STI &

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# Content

- Overview and challenges
- Target technologies
  - Graphite Target
  - Liquid Lead Target
  - Fluidized W Target
- Conclusions

# Target system

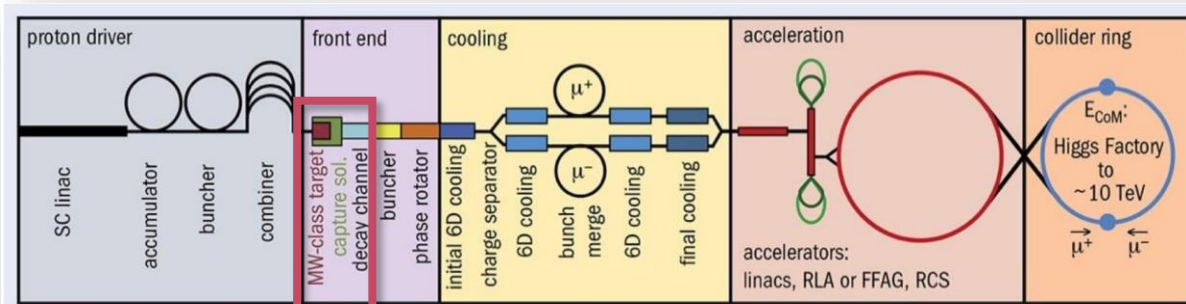
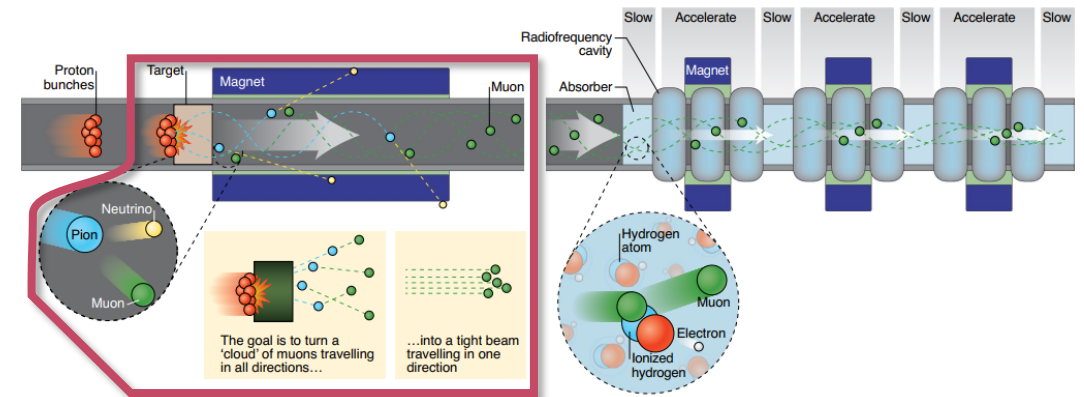


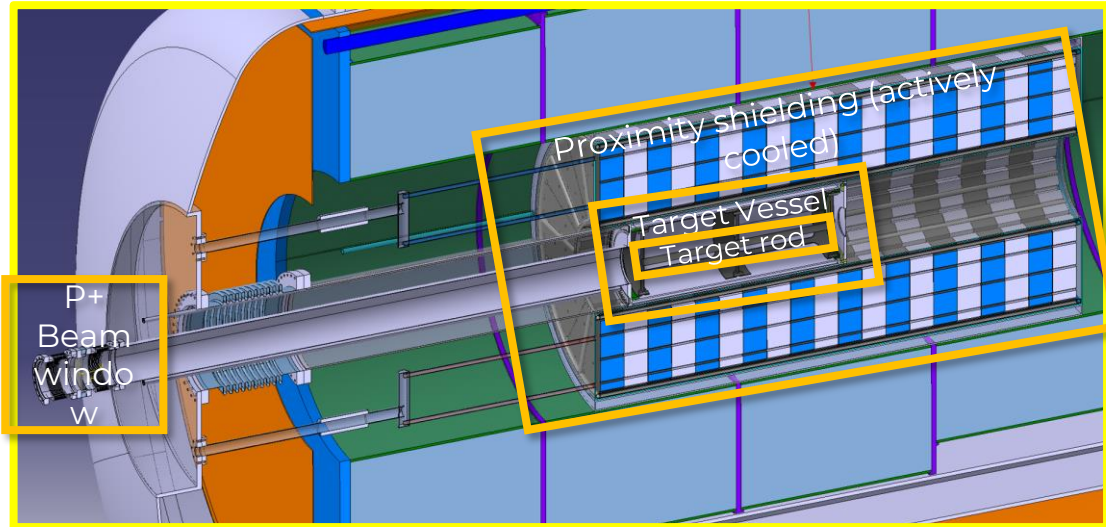
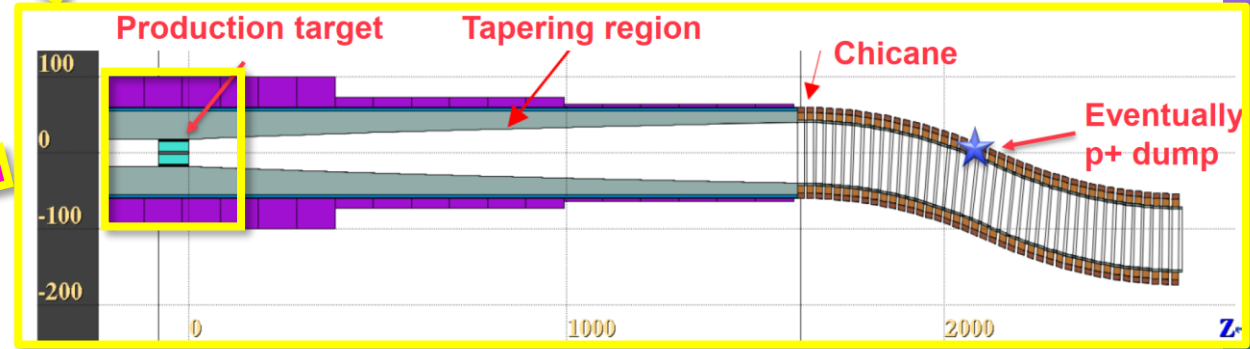
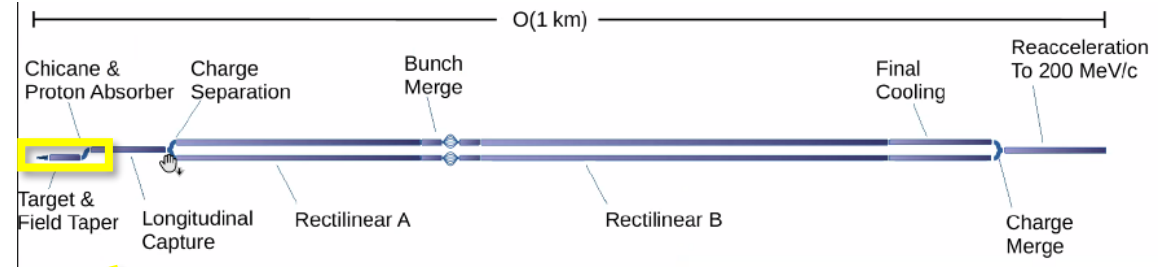
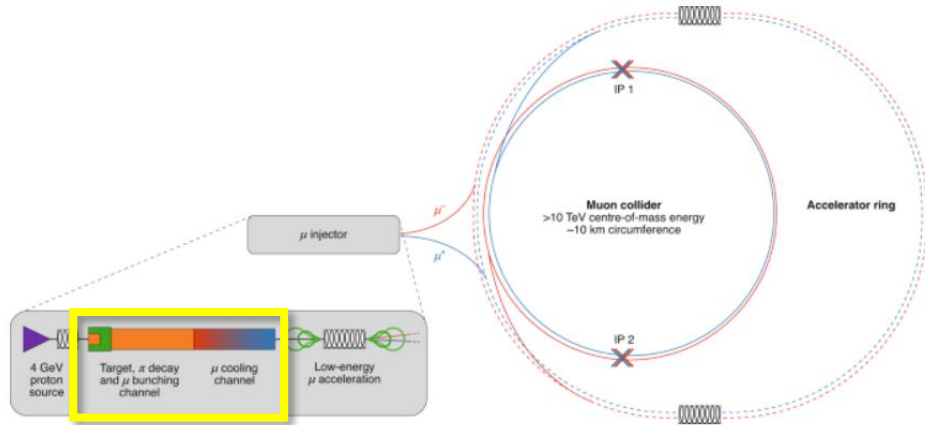
Fig. 2: Layout of the Muon Collider complex as elaborated by the MAP



## Target system development

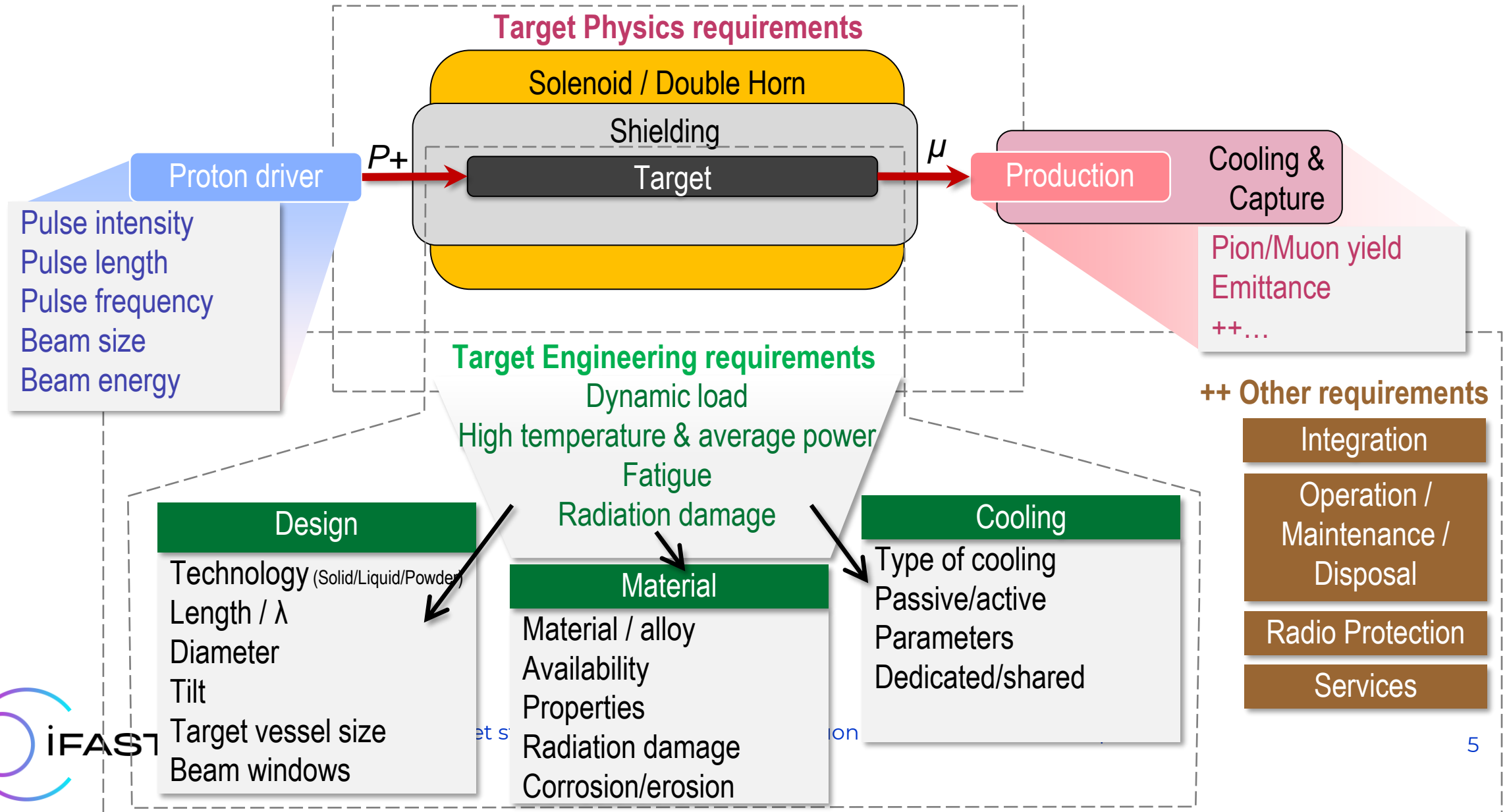
- Establish a baseline target
- Identify technological limits and R&D.
- Define a system conceptual design
- Estimate pion yield, target lifetime, heat load on the surrounding magnets.
- Define the required shielding and associated magnet aperture

# Target system & BIDs in the Frontend



- Target
- Target vessel
- Proximity shielding
- P+ beam window
- P+ dump
- Shielding in tapering and chiane

# Target & target systems considerations



# Target & target systems considerations

- **Beam Pulse Impact:** 2 ns pulses induce intense thermal shocks, particularly problematic for solid targets.
- **Thermal Load:** 110-220 kW on the target (for a 2-4 MW proton driver) and up to 34% of stored beam energy deposited on nearby shielding.
- **Radiation Damage:** Significant POT leads to irradiation damage (e.g. dpa, gas production) and risk of structural degradation due to conductivity loss and embrittlement. Reduces lifetimes of the materials/components.
- **Integration:** Combining the high-radiation environment of the target with the superconducting solenoids requires complex shielding and cryostat design. Integration of the shielding and target cooling services inside the cryostat.
- **Target Accessibility:** Target exchange must be feasible (due to limited life-time of the target or possible target failures) without completely dismantle the cryostat and/or remove all the surrounding shielding.
- **Proton Beam Window:** High DPA (displacement per atom) exposure requires robust, low-Z materials (e.g., beryllium) and active cooling.
- **Maturity of technologies:** Good experience with graphite solid targets. Fluidized W or liquid lead concepts require the development of a new modelling framework and R&D

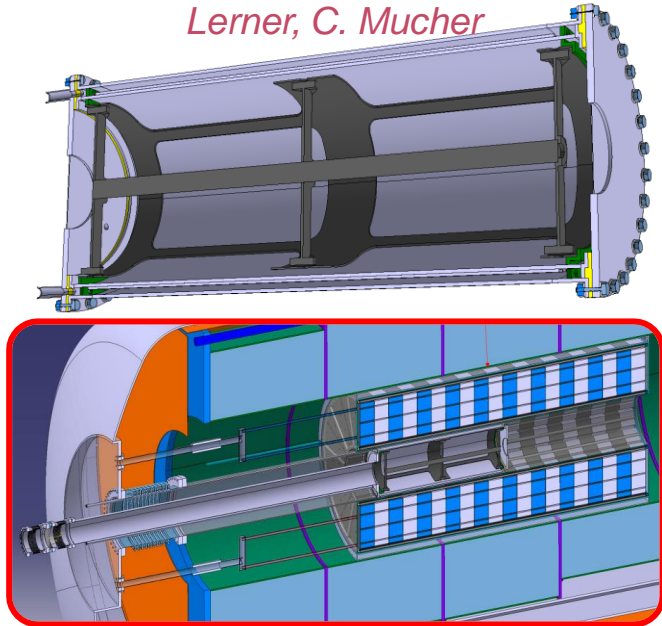
Parameter	Baseline (2MW)	Option A (4MW)	Option B (4MW)
Kinetic Energy [GeV]	5	10	10
Beam size [mm]	5	5	7.5
Bunch length [ns]	2	2	2
Bunch intensity [ $10^{14}$ ppb]	5	5	5
Bunch Frequency [Hz]	5	5	5

# Targetry options

CERN leading C-Target system studies & liquid-Pb option with ENEA. RAL & Warwick University leading fluidized W option.

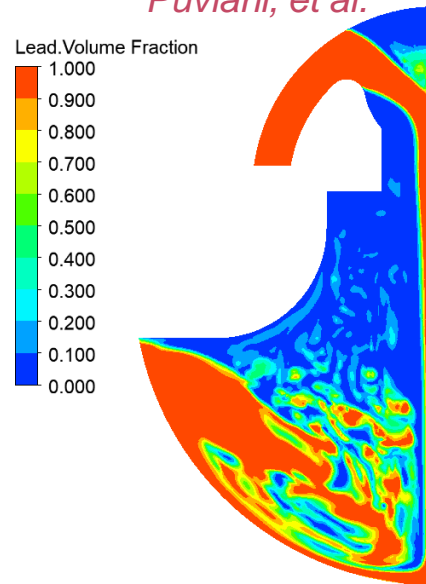
## C-Target & target system CERN

*S. Cândido, R. F. Ximenes, M. Calviani, D. Calzolari, A. Lechner, F. Saura, J. Manczak, G. Lerner, C. Mucher*



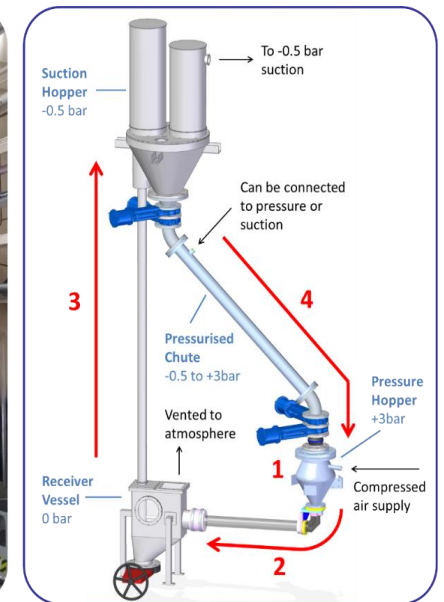
## Liquid Pb Target ENEA & CERN

*C. Carrelli, L. Tricarico, M. Tarantino, I. Di Piazza, P.C. Puviani, et al.*



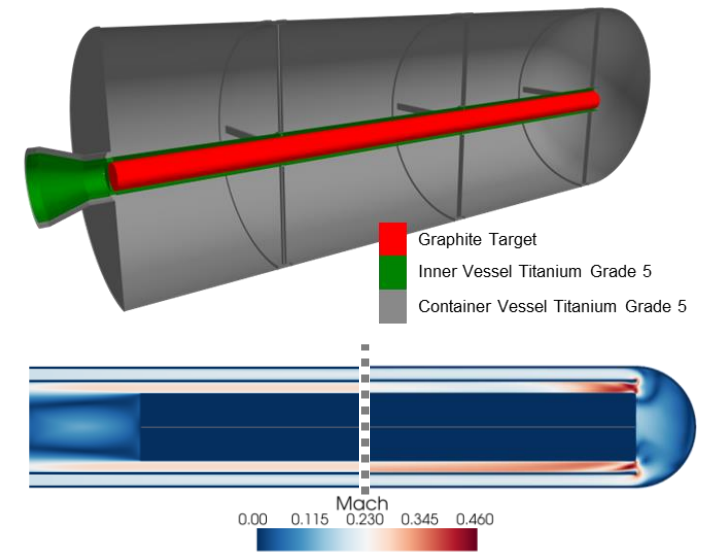
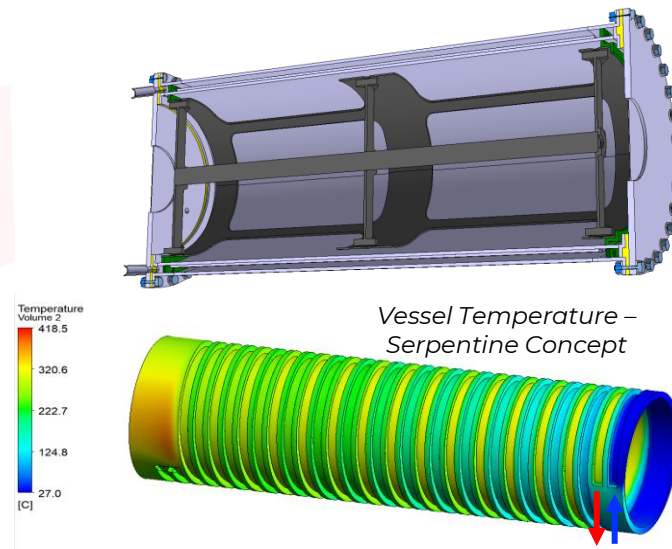
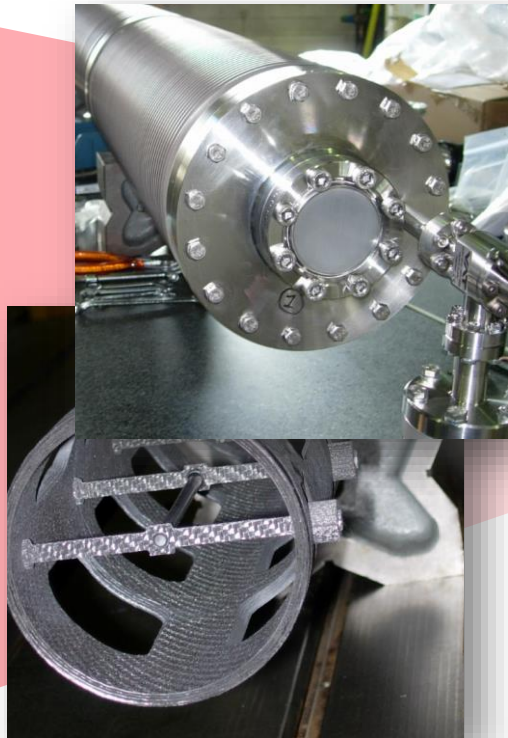
## Fluidized W-Target RAL & Warwick Uni.

*B. Suitters, C. Densham, J.J. Back, W. Bishop, D. Wilcox, et al.*



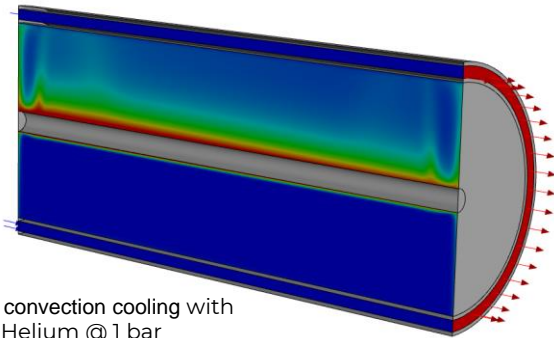
# Graphite Target – Evolution of the Conceptual Designs

- Inspiration on other C-Targets. E.g. CNGS, T2K, LBNF...



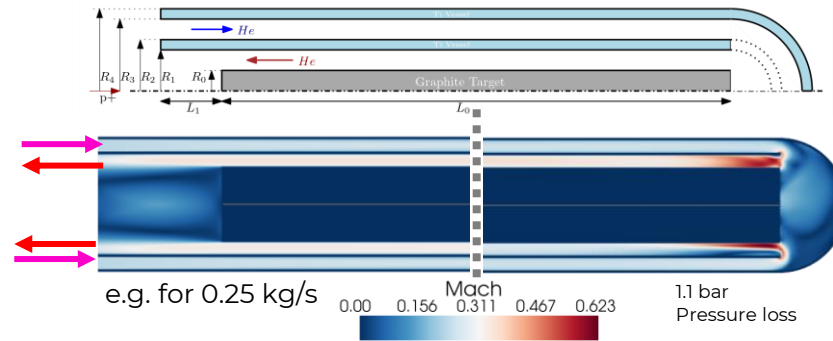
# Carbon Target – Cooling

Baseline 2 MW (natural convection)



Natural convection cooling with Helium @ 1 bar

4 MW (option A / B with forced convection)



	Option A	Option B
(mm)	10 GeV 5mm	10 GeV 7.5mm
R0	15	22.5
R1	20	27.5
R2	21	28.5
R3	26	33.5
R4	27	34.5
L0	800	800
L1	50	50

■ Fs=1.25  
■ Physical Limit

HTC is cross-checked with CHT flow simulation, analytical (Gnielinski correlation) gives <5% difference to numerical

Properties	Value
Density [kg/m <sup>3</sup> ]	1830
Tensile Yield Strength [MPa]	29.7
Sublimation T [°C]	3330

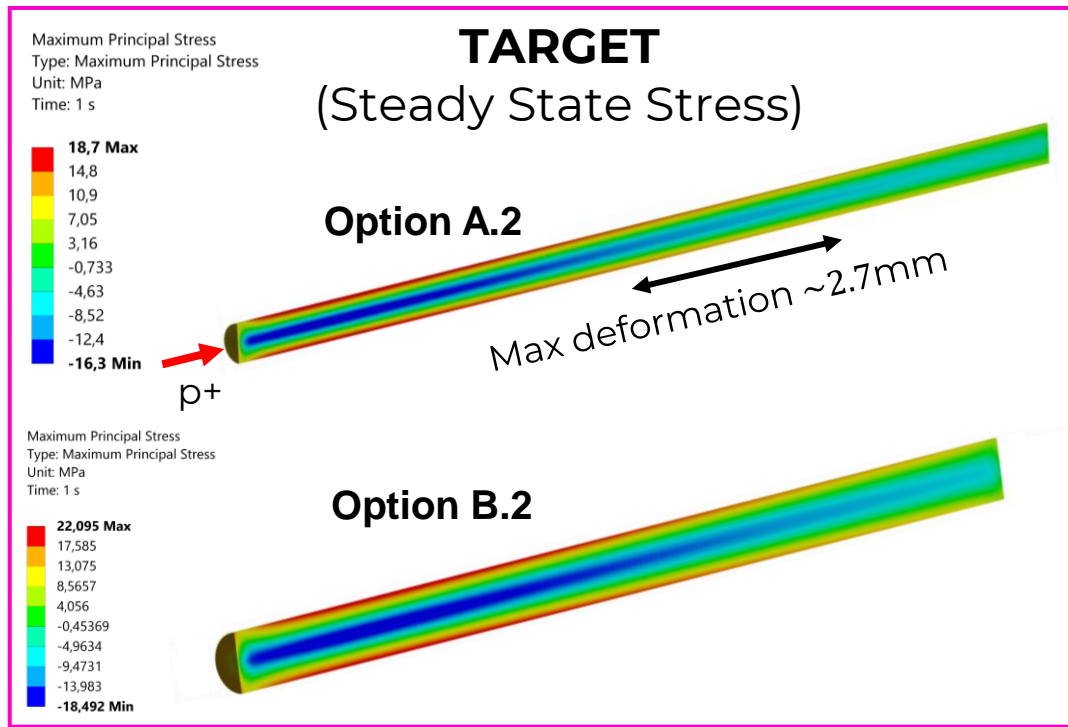
#	Energy [GeV]	Power [MW]	Beam sigma [mm]	Target R0 [mm]	Mass flow rate [kg/s]	Mach	He [bar]	HTC [W/m <sup>2</sup> °C]	Tmax [°C]	Tsurf [°C]	(SS) Principal stress [MPa]
1	5	2	5	15	Natural Convection	NA	1	33	2422	2014	19.23
2	10	4	5	15	Natural Convection	NA	1	33	3315	2456	28.25
A.1	10	4	5	15	0.25	0.28	10	4797	1448	652	17.66
A.2	10	4	5	15	0.20	0.22	10	3898	1516	763	18.74
A.3	10	4	5	15	0.10	0.11	10	2255	2096	1240	25.69
B.1	10	4	7.5	22.5	0.36	0.28	10	4792	1392	548	19.52
B.1	10	4	7.5	22.5	0.30	0.23	10	4135	1540	640	21.35
B.2	10	4	7.5	22.5	0.25	0.20	10	3420	1619	683	22.42

← Baseline 2 MW

Best candidate parameters for 4 MW

# Carbon Target – Steady-state conditions

- Deformation inner vessel ~0.51mm and C-Target deforms ~2.7mm → **Support system needs to be constrained and tested**



# Carbon Target – Thermal shock

Heating is abrupt  $\Rightarrow$  wave launches  $\Rightarrow$  **dynamic stress**

Elastic-wave transit time is the radial distance

Graphite  $c_{\text{wave}} \sim 2,600$  m/s  $\rightarrow$  elastic wave  $\tau \approx 5.8 \mu\text{s} > 2$  ns (pulse length)

From LS Dyna explicit structural simulation of stress waves propagation in graphite for baseline:

GRAPHITE R 45550

Polycrystalline SGL

$$E_d = 11.5\text{GPa}$$

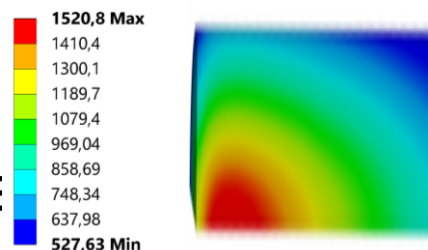
## C-Target 2MW

Alternant stress (MPa) 0.7

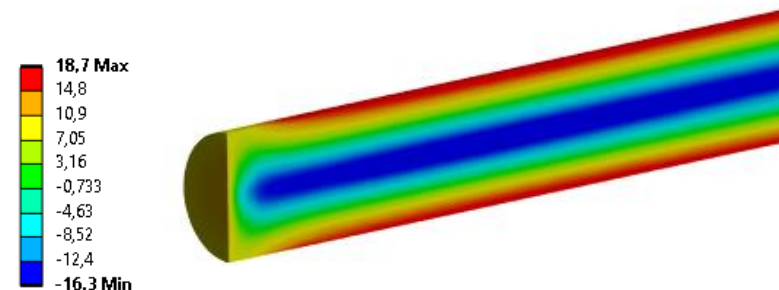
Average stress (MPa) 22.5

Beam size	$T_{max}$ (°C) steady	$T_{min}$ (°C)	$T_{max}$ (°C) surface	$T_{core}$ (°C)	$T_{peak}$ (°C)	$\Delta T$ (°C)	Dynamic Stress [MPa]	Peak Principal stress [MPa]
5mm	1527.1	527.6	872.71	1548.7	1604.9	56.2	3.23	25.2
7.5mm	1517.0	496.08	647.98	1514.2	1543.2	29.0	1.67	24.87

Temperature °C



Stress MPa



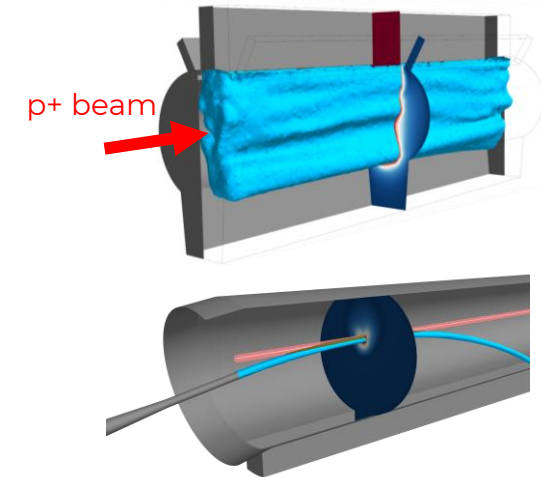
# Liquid Pb Target – Pros & Cons

## Opportunities

- **Known** liquid-Pb / LBE thermo-hydraulics
- **Cooling** outside vacuum chamber.
- **Radioisotopes** mostly **retained**.
- **No degradation** of target material.
- **Synergies** between different projects at CERN such as  **FCCee**.

## Challenges

- Liquid-Pb containment **vessel and windows** (material, temperatures, DPA).
- **MHD** interaction.
- Cavitation-induced **erosion**.
- **Temperature and dynamic effects**.
- Dynamic multi-phase flow **simulation complexity**



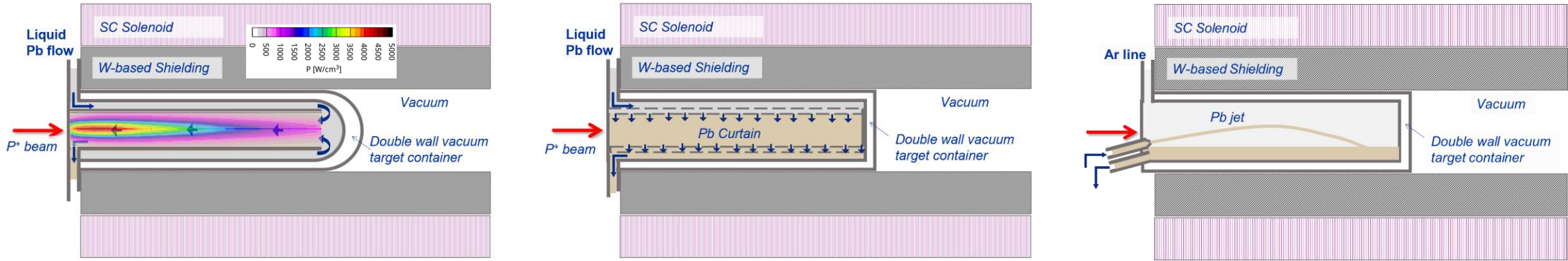
### Conceptual designs

- Pipe flow.
- **Vertical curtain.**
- **Jet stream.**



*C. Carrelli, L. Tricarico, M. Tarantino, I. Di Piazza, P.C. Puviani, et al.*

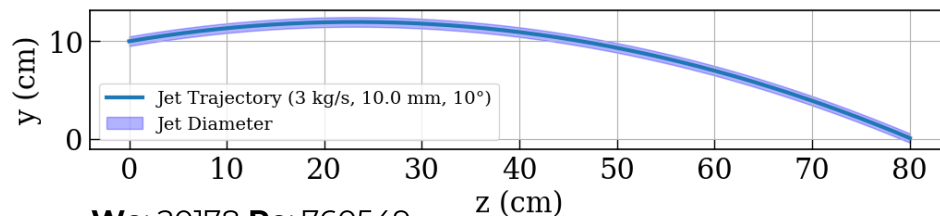
# Liquid Pb Target - Evolution of the Conceptual Designs



- **Initial concept:** presented very high **magneto hydrodynamic losses**. Besides challenging high temperature vessel and windows in contact with lead.
- **Curtain concept:** **was found to reduce the muon/pion yield** and **increases the radiation load to the HTS coils**.
  - The reduction of the yield is **greatly due to the necessary vertical height to form the curtain**.
- A **liquid jet is proposed** instead. This type of jet solution as been explored for intercepting beams, e.g., MERIT experiment (HIGH INTENSITY LIQUID MERCURY TARGET EXPERIMENT AT THE CERN PS)

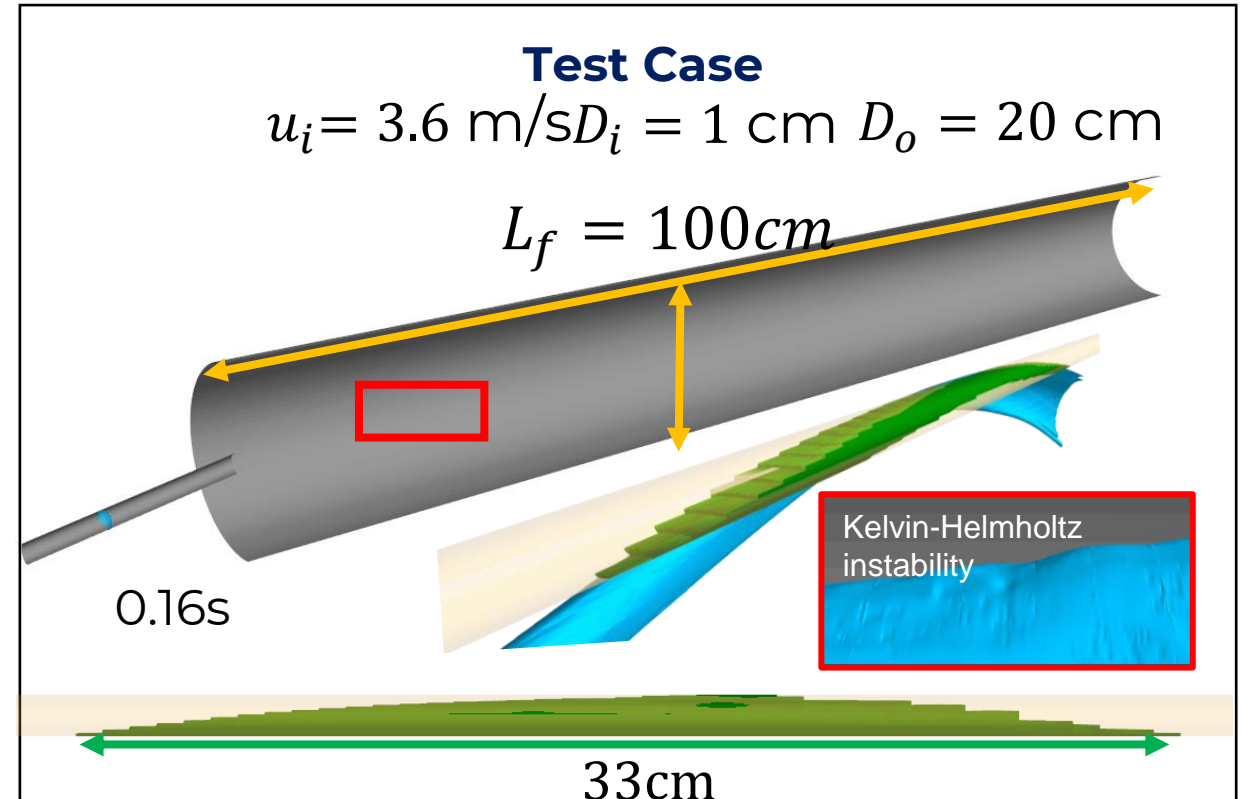
# Liquid Pb Target – Jet Concept

- The **required length and radius for a liquid lead rod** were calculated by re-scaling the graphite rod dimensions, based on the ratio of inelastic scattering lengths for 5 GeV protons<sup>1</sup>.
- Considering a Ballistic Trajectory, based on Newtonian motion equations we predict 1<sup>st</sup> the trajectory analytically:



We: 20178 Re: 760549

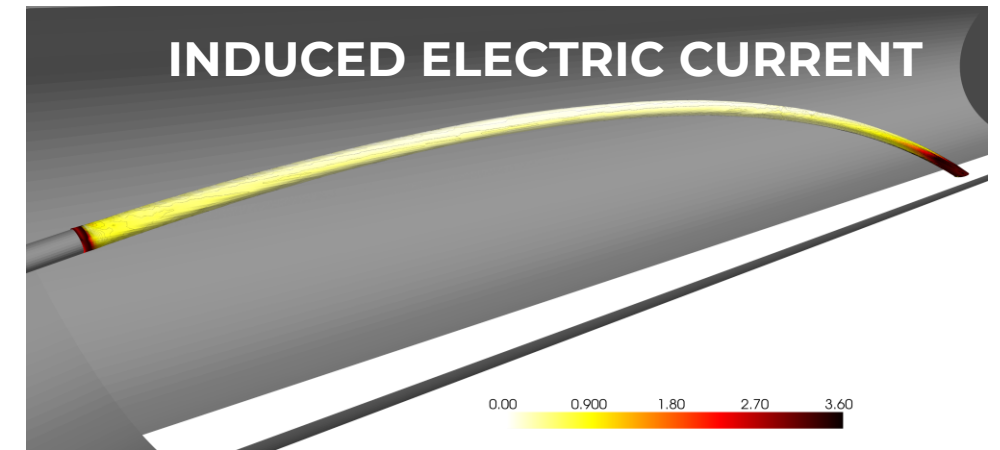
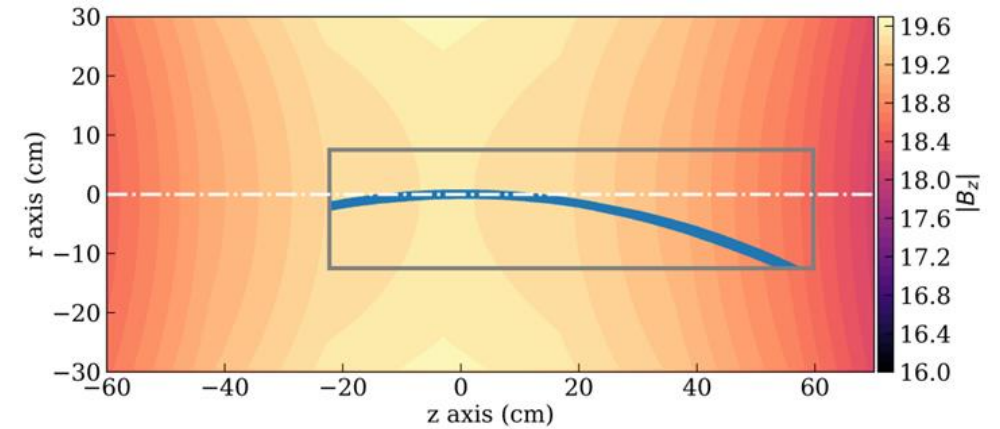
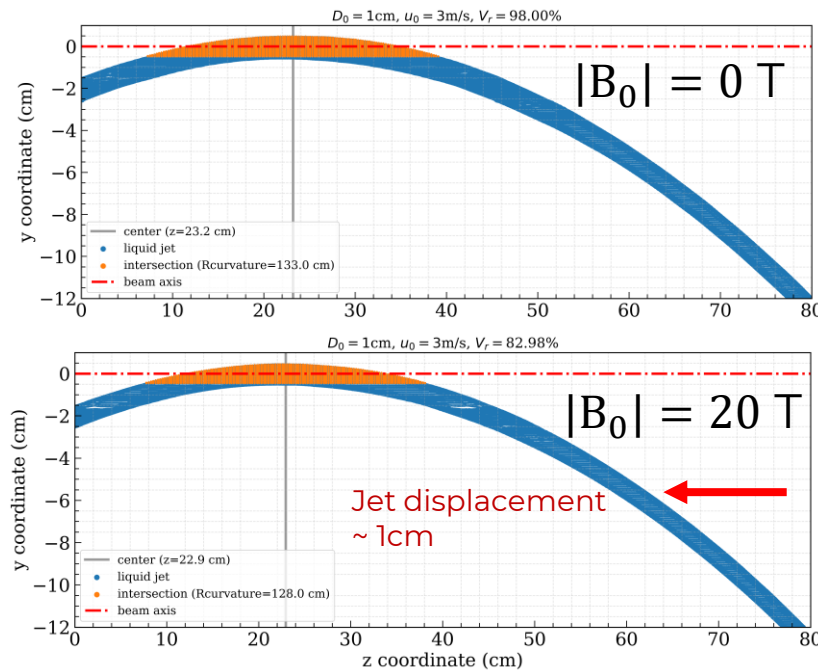
$L_{breakup}$ : 589.3 [cm]  $\gg$  L Target region



# Liquid Pb Target – Jet Concept

## Interaction with the magnetic field

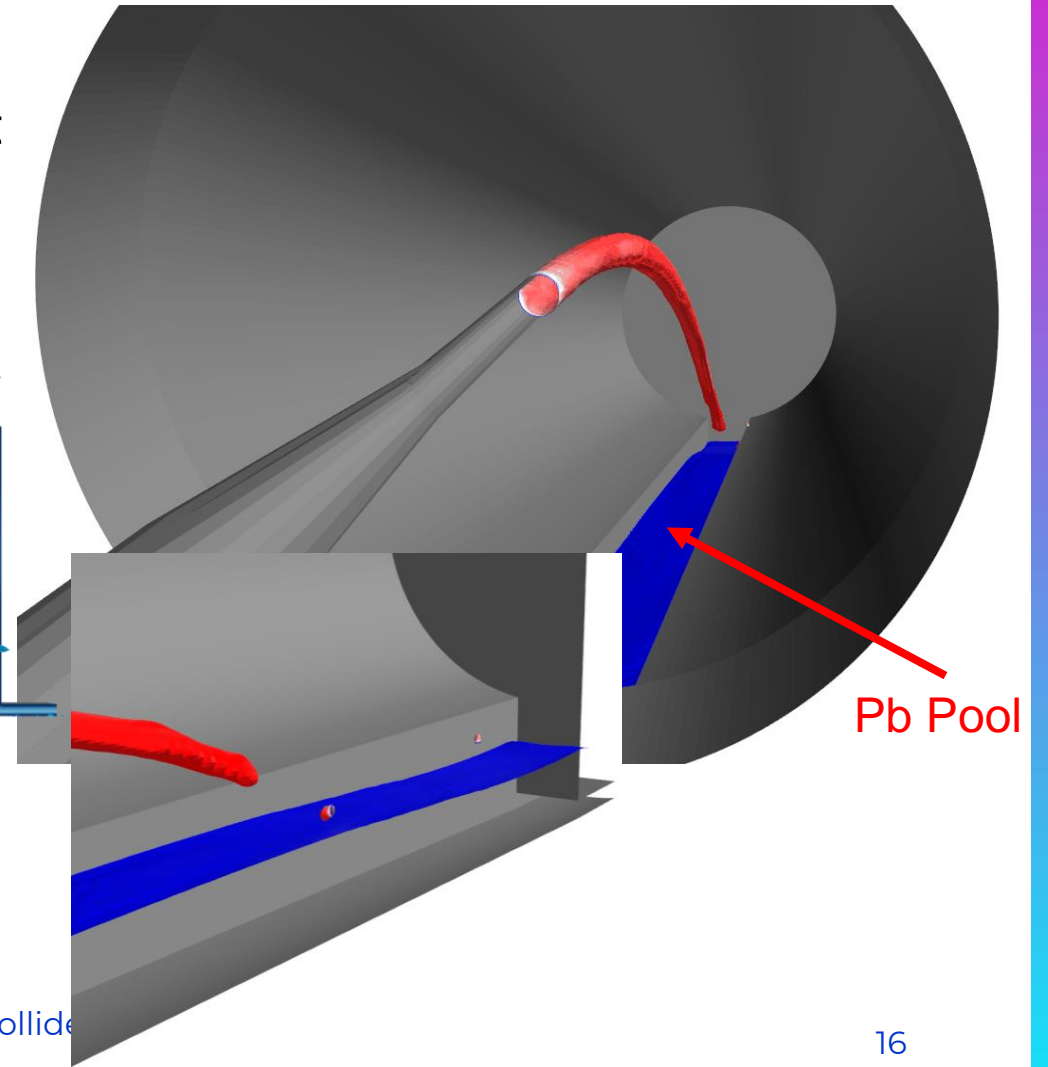
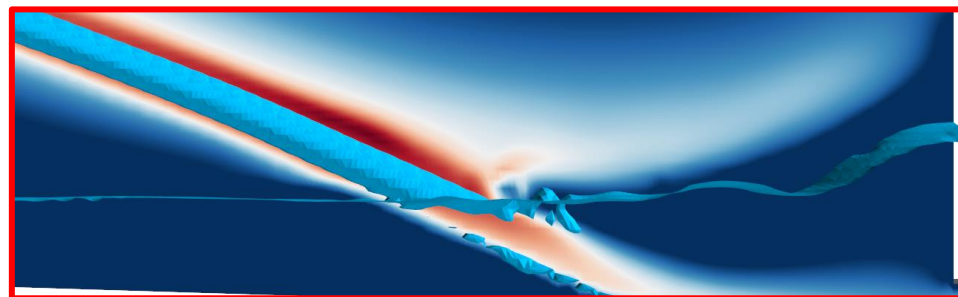
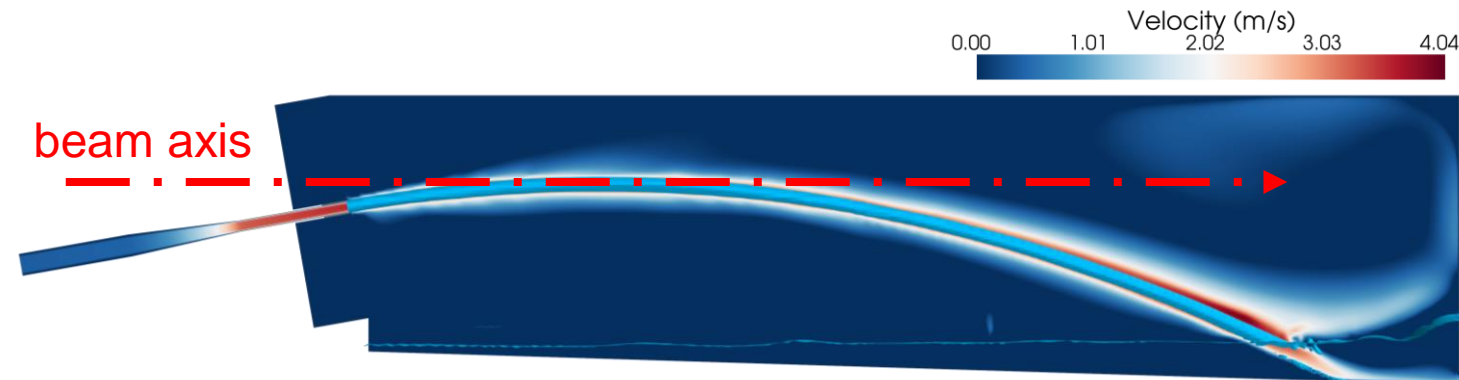
- Effects due the magnetic field are less abrupt comparing with the vertical curtain, but there's an effect of **break on the velocity** → **Reducing cross section and lenght**



# Liquid Pb Target – Jet Concept

## Fluid dynamic calculations

- Due to the necessary relative high velocity of the jet (4m/s) at the end, a **pool of liquid lead is considered in order to absorb the kinetic energy** of the jet and not have a direct contact with the wall.

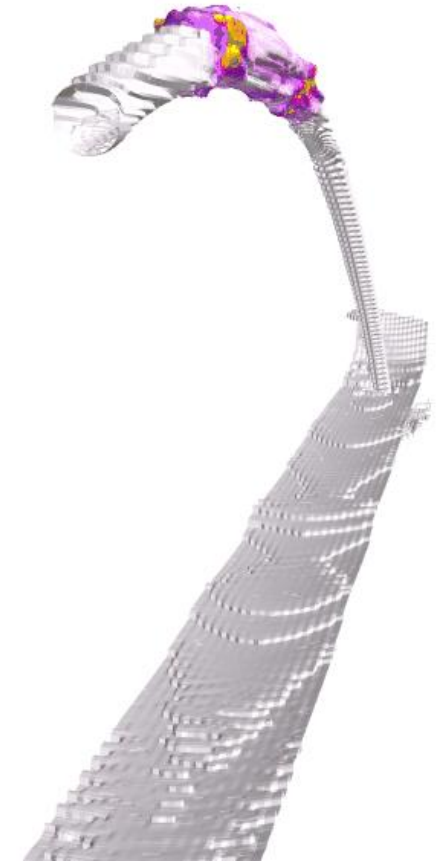
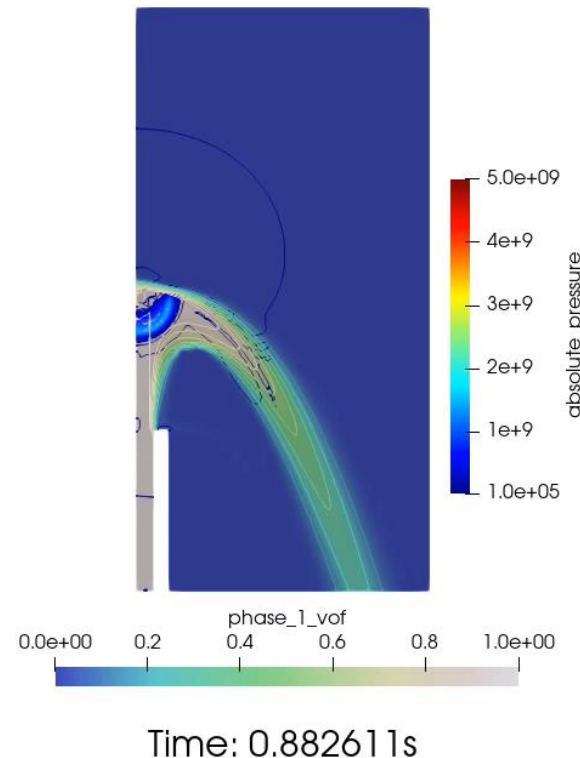


# Liquid Pb Target – Jet Concept

## Shock-wave propagation

### Shockwave and cavitation: set up

- Over pressure of 5GPa resulting from  $1e18$  [W m<sup>-3</sup>] pick deposition – (starting with 2 MW conditions).
- Patch pressure at 5GPa into the interaction zone.
- Compressible liquid lead according to Tait EOS.
- Cavitation model for liquid lead under 10 Pa.
- Incompressible argon and lead vapour.
- Isothermal VOF model.
- Time step 10ns.



Simulation trials on vertical and horizontal jets

# Fluidised W Target – Pros & Cons

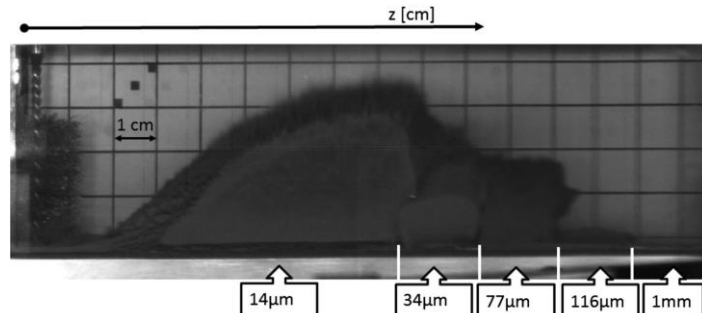
## Advantages

- No cavitation, corrosion, radiochemistry damage.
- High thermal-shock resistance.
- Heat removal.

## Challenges

- Erosion & powder handling and reliability.
- Reduced **experience** in operational facilities

## Offline tests at RAL & HiRadMat beam test

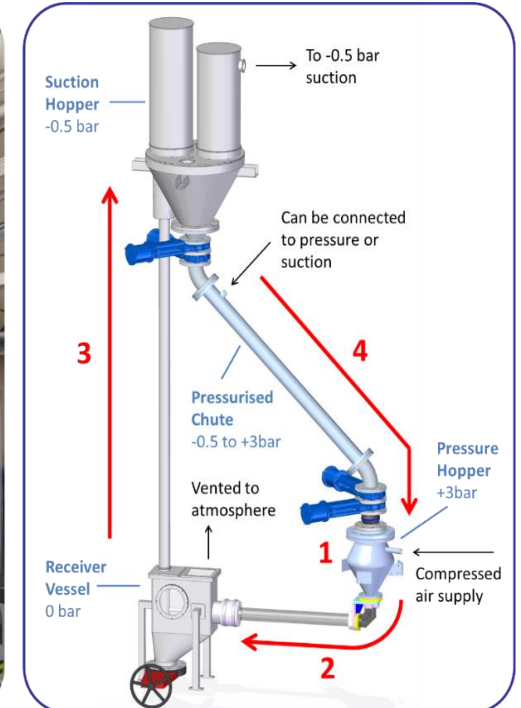


Response of various size spherical tungsten particles to  $2 \times 10^{11}$  p+ at HiRadMat (CERN)

Target studies for the International Muon Collider Collaboration | NuFact25



Test rig built and operated at Rutherford Appleton Laboratory from 2009-2018

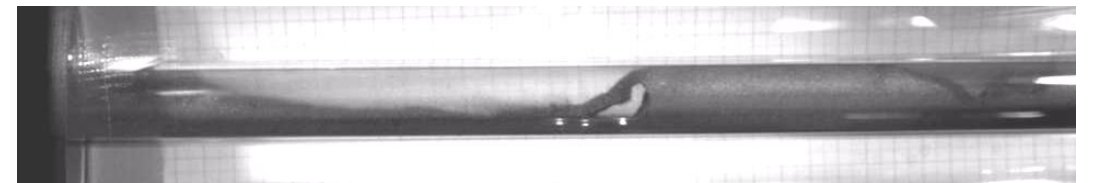
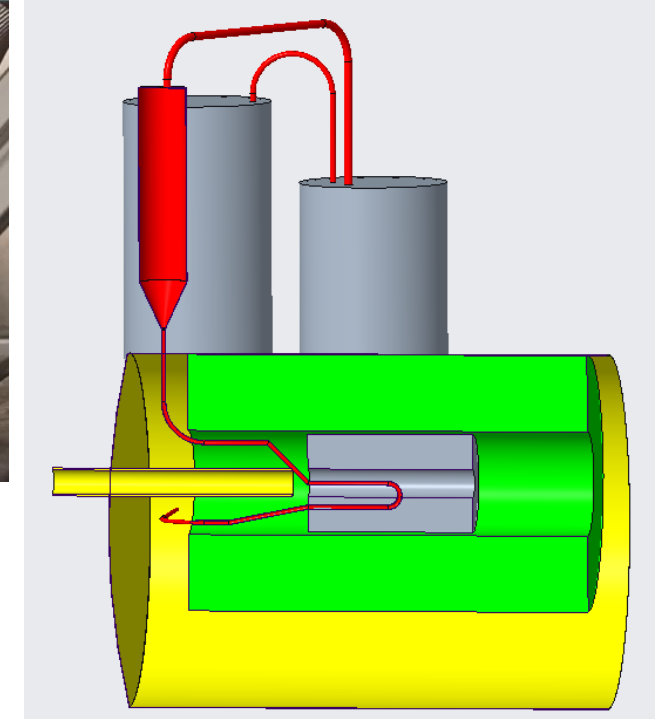


*B. Suitters, C. Densham, J.J. Back, W. Bishop, D. Wilcox, et al.*

# Fluidised W Target – Overview of the studies

## Focus on R&D

- **Heat deposition:** Design in parallel with Physics optimisation
- **Pressure:** Minimise piping length, test with off-line rig
- **Erosion:** Ongoing work to assess at University of Sheffield
- **Process design**
  - Use STFC expertise in facility design
  - Industrial expertise pneumatic conveying and powder handling plant
  - Offline Testing!



# Fluidised W Target – Status

- Royce Institute at Sheffield are actively engaging on **materials testing for different grades of powders**. Aiming at flowability and friction characteristics of the powders
- The **simulation** effort is ongoing with new Discrete Element Model solver ANSYS Rocky.
- Will is working on **FLUKA studies of more integrated, "engineering reality" geometries**.
- We have a **top-level cost estimate of an experimental rig**

# Conclusions

- **A future TeV Muon Collider requires a MW-class production Target, exposed to high instantaneous and average power.**
- **Within the International Muon Collider Collaboration, multiple Target technologies are being pursued.**
  - Graphite Target is the baseline for 2 MW. Profits from existing operational experience.
  - Liquid lead and fluidized W being explored as high-power (4 MW) alternatives . Extensive modelling ongoing to identify feasibility and R&D threads.

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**Thank you!**

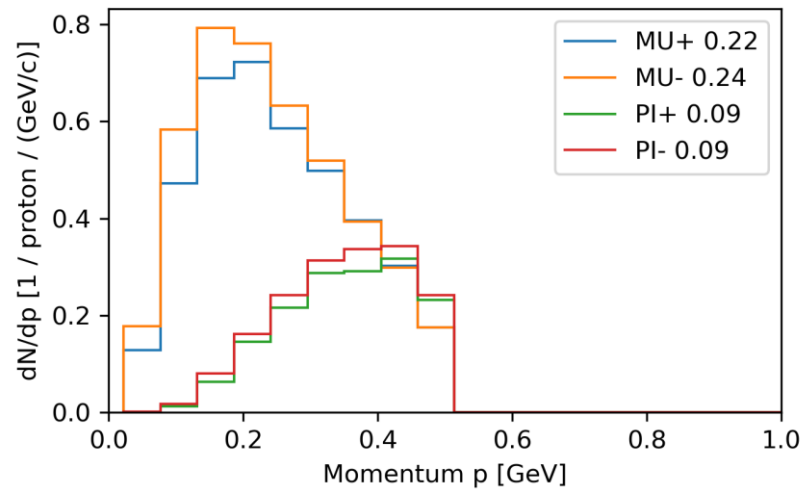


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# Target material comparison – yield

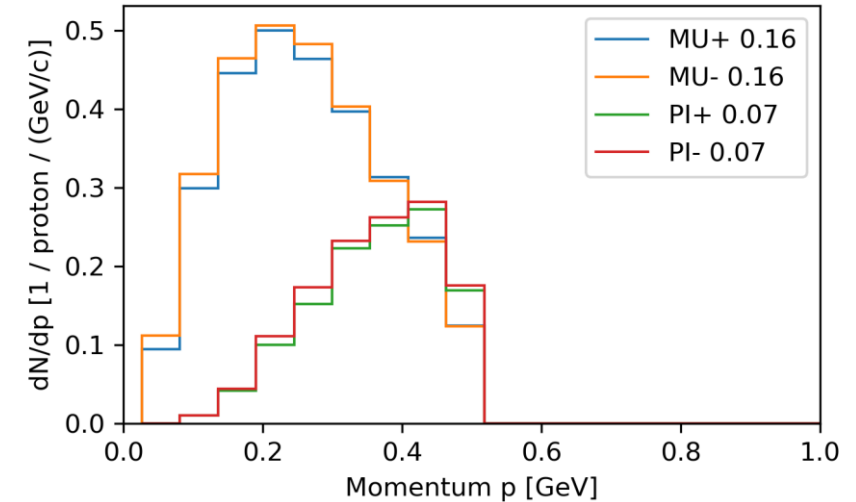
Calculated at the end of the tapering region

## Lead rod

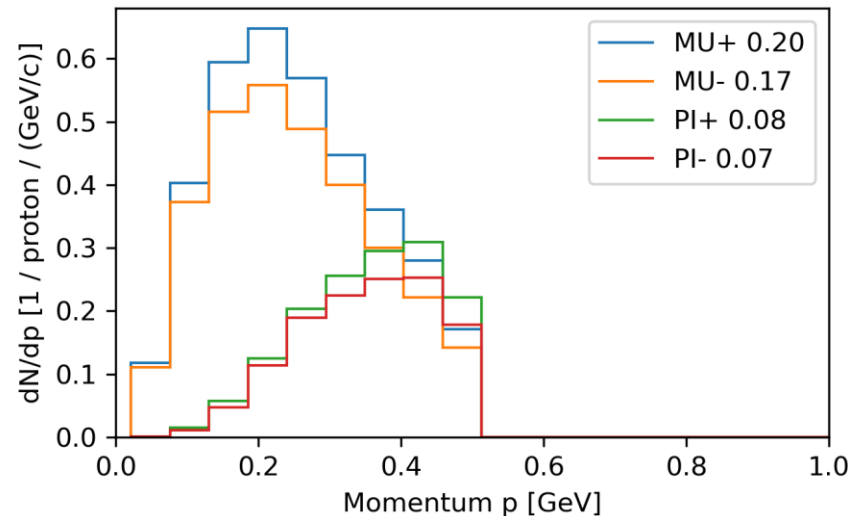


The graphite could still be a valid option for 4 MW beam, but the target cooling has to be modified

## Lead curtain



## Graphite rod

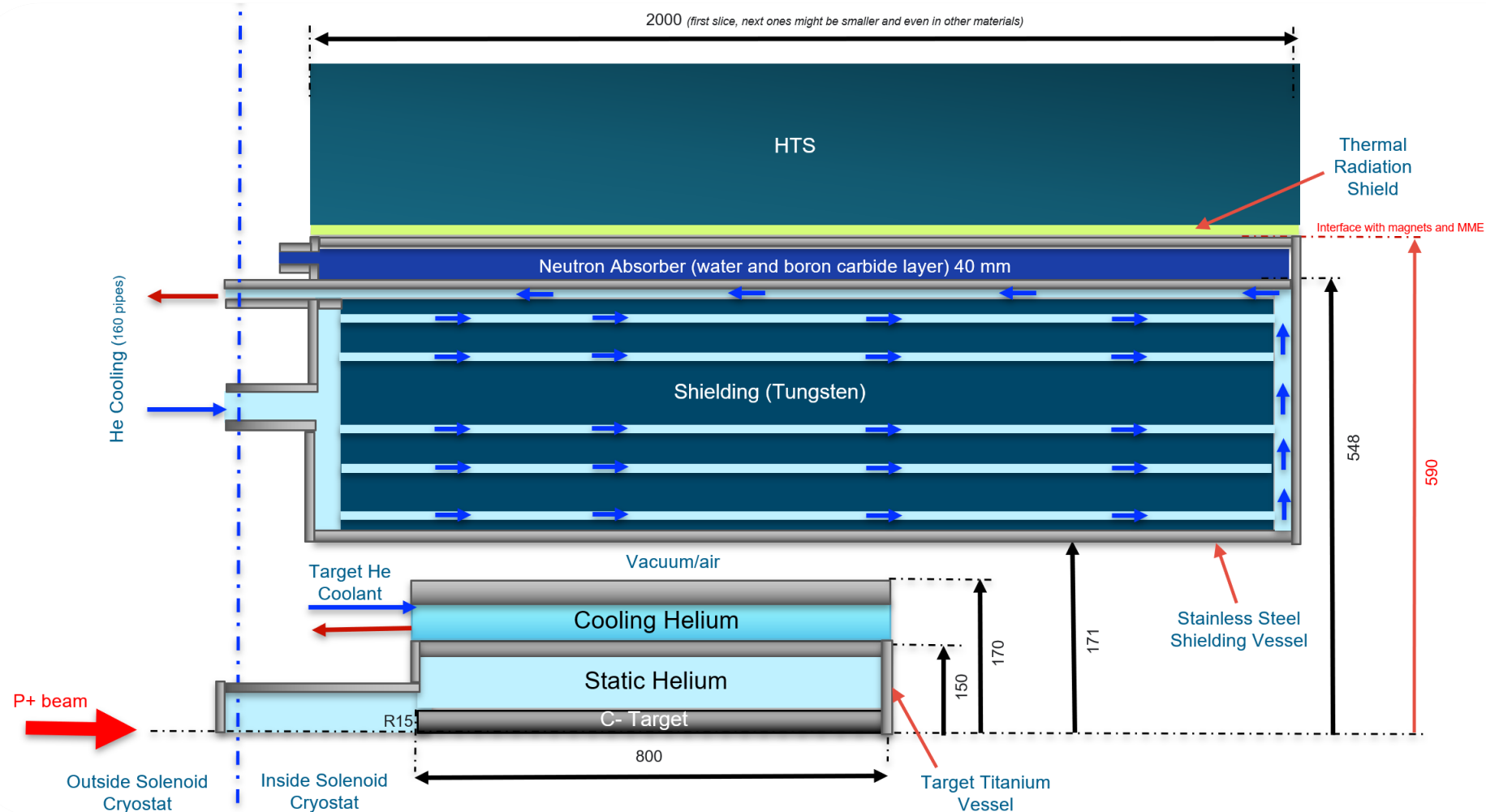


Liquid lead rod gives significantly better yields in comparison with graphite!  
Its more realistic version will in a form of a jet be studied in the future.

A curtain compromises the yield already with an idealized geometry simulations! Realistically, the loss could be even greater

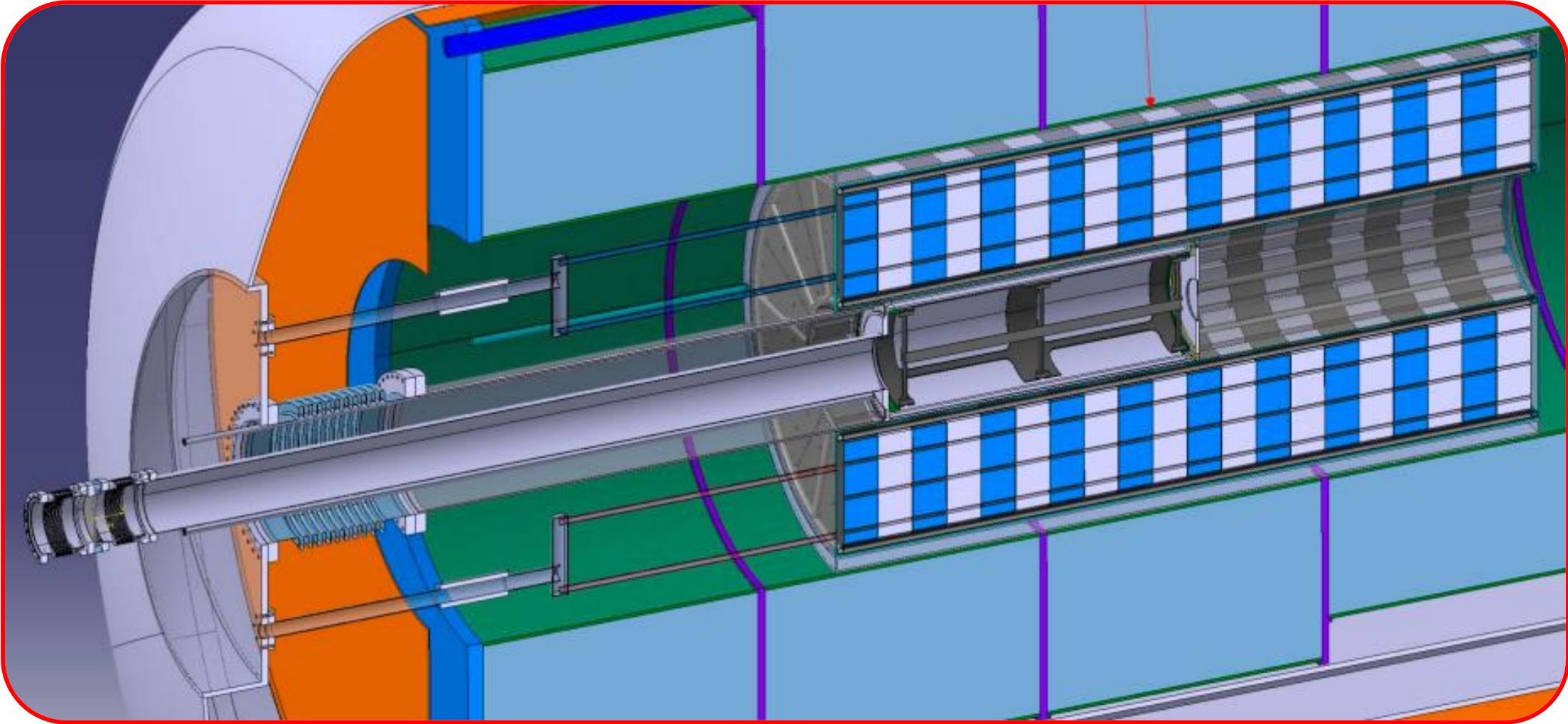


# Target System (for the C-Target)



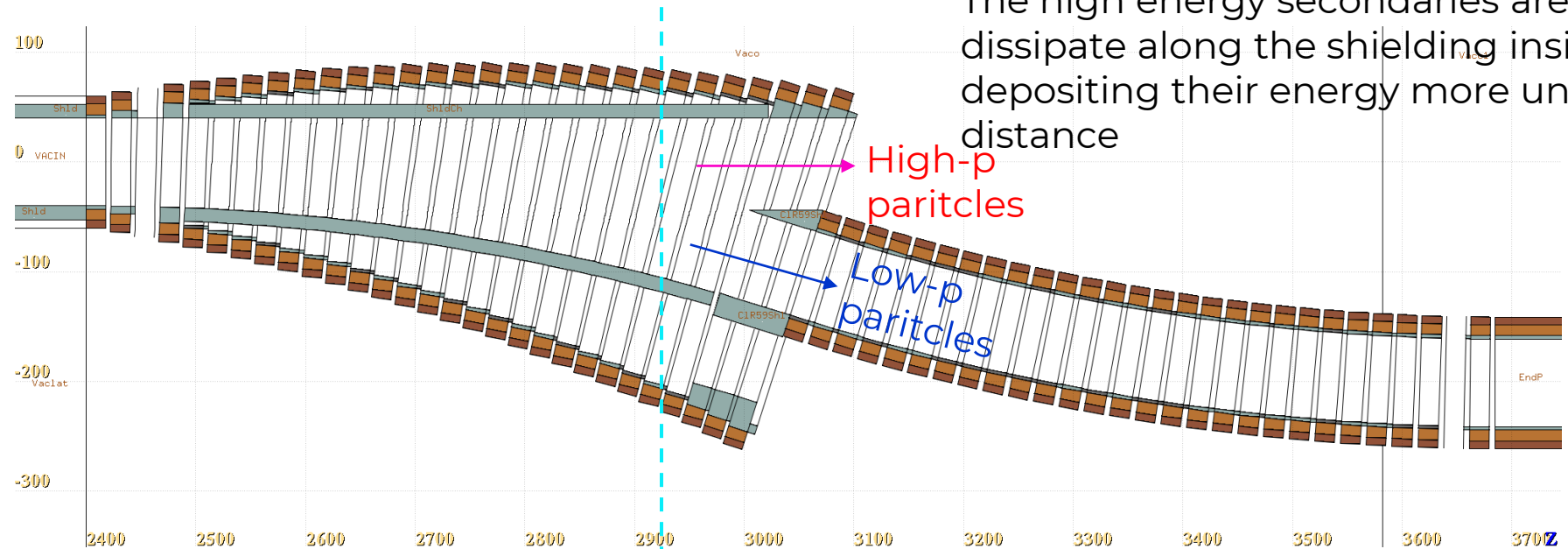
MuC target & shielding schematic (not at scale) [units in mm]

# Target System (Image from Antti)



# Chicane idea

The high energy secondaries are expected to dissipate along the shielding inside the chicane, depositing their energy more uniformly on a wider distance



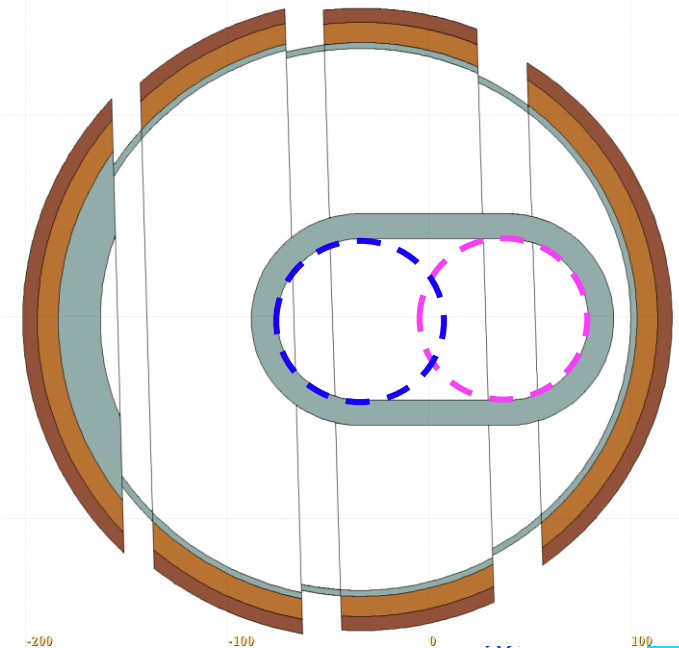
High-p particles

Low-p particles

**Main challenge:**  
Very large magnet apertures would be required! It is likely that the magnets would have to be normal conducting due to radiation load.

One cylinder is the extension of the tapering final aperture

The second one follows the curvature of the chicane, always centered around the magnet center



# Carbon Target - Supports

